Evaluating the Impact of Social Selfishness on the Epidemic Routing in Delay Tolerant Networks

Yong Li, *Student Member, IEEE,* Pan Hui, Depeng Jin, *Member, IEEE,* Li Su, and Lieguang Zeng

***Abstract*—To cope with the uncertainty of transmission opportunities between mobile nodes, Delay Tolerant Networks (DTN) routing exploits opportunistic forwarding mechanism. This mechanism requires nodes to forward messages in a cooperative and altruistic way. However, in the real world, most of the nodes exhibit selfish behaviors such as individual and social selfishness. In this paper, we investigate the problem of how social selfishness influences the performance of epidemic routing in DTN. First, we model the message delivery process with social selfishness as a two dimensional continuous time Markov chain. Then, we obtain the system performance of message delivery delay and delivery cost by explicit expressions. Numerical results show that DTN is quite robust to social selfishness, which increases the message delivery delay, but there is more reducing of delivery cost.**

***Index Terms*—Delay tolerant networks, social selfishness, performance evaluation.**

I. Introduction

In Delay Tolerant Networks (DTNs), an end-to-end path between the communication source and destination is not always available [1]. Therefore, DTN routing algorithms are quite different from these for Internet and traditional ad hoc networks [2]. The new mechanism for routing is called store-carry-and-forward [3], which exploits the opportunistic contacts between nodes and mobility to relay and carry messages respectively. Consequently, it requires the nodes to forward messages in a cooperative and altruistic way. For example, when the next hop is not immediately available for delivering a message, the node would utilize its own limited buffer to store the message, carry it along on the move, and forward it to other appropriate nodes which help to transmit the message further. The most typical algorithm is epidemic routing [4], which requires two nodes to exchange messages that the other has not seen yet when they have a communication contact.

However, nodes are selfish in a large number of DTNs. For example, in mobile social networks, people as the nodes form one or more individuals with similar interests or communities using mobile phones [5]. From the viewpoint of an individual, the node is unwilling to relay and store messages for others in order to conserve the limited buffer and power resources [6].

Manuscript received March 28, 2010. The associate editor coordinating the review of this letter and approving it for publication was H. Yousefi'zadeh.

This work is supported by National Major Scientific and Technological Specialized Project (No. 2010ZX03004-002-02), National Basic Research Program (No. 2007CB310701)and National High Technology Research and Development Program (No. 2008AA01Z107 and No. 2008AA01A331), PCSIRT and TNLIST.

Y. Li, D. Jin, L. Su, and L. Zeng are with the State Key Laboratory on Microwave and Digital Communications, Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China (e-mail: jindp@mail.tsinghua.edu.cn).

P. Hui is with Deutsche Telekom Laboratories/TU-Berlin, Ernst-Reuter-Platz 7, 10587 Berlin, Germany.

Digital Object Identifier 10.1109/LCOMM.2010.093010.100492

While from the aspect of community, it has greater incentive to forward messages from the nodes in the same community, but less interest to forward the messages from the nodes outside its community [5]. These two types of selfishness are called *individual selfishness* and *social selfishness*, respectively [7]. Most of the current works on DTN either ignore the node selfishness or only consider the *individual selfishness* [7][8]. Our work aims to study how *social selfishness* affects the performance of message delivery in a socially selfish DTN.

In this paper, we focus on the performance evaluation of epidemic routing in DTN by considering the case that nodes form two communities, and they forward messages following the behaviors of social selfishness. We model the epidemic routing with social selfishness as a two dimensional continuous time Markov chain. Based on this model, we derive the system performance of both message delivery delay and delivery cost. By setting the parameters obtained from the real trace, we give numerical results. The results show that social selfishness increases the message delivery delay, and at the same time decreases the delivery cost, which demonstrates DTN is robust to social selfishness.

II. Modeling the Social Selfishness

A. System Model

In our work, nodes are partitioned into non-overlapping communities. This may result from their grouping in accordance to their professional affiliation, as in [10]. We model the socially selfish DTN as two communities of wireless mobile nodes denoted by V_1 and V_2, with $V_1 = \{1, 2, ..., M\}$, $V_2 = \{1, 2, ..., N\}$, respectively. Since the density of nodes is sparse in DTN, they can communicate only when they move into the transmission range of each other, which means a communication contact. We assume the occurrence of the contacts between any two nodes follows Poisson distribution, which is validated by [9]. Consequently, the inter-contact time between two nodes follows exponential distribution with some parameter $\tilde{\lambda}$. Considering the different distributions of inter-contact time of inter-community and intra-community reported in [10], we set the contact rate of the nodes that are *inside* the same community to be λ_i, and set the contact rate of the nodes with others *outside* their community to be λ_o. At the same time, there is a source node and a destination node in the system. They do not belong to communities V_1 and V_2, and encounter any other nodes in these two communities with rate of λ.

In the epidemic routing, when a message arrives at an intermediate node, the node forwards the message to all its neighbors. However, the nodes' social selfishness will influence the message forwarding when a node without any message encounters a node with a message. If these two nodes

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are in the same community, the message is forwarded with probability p_i. Otherwise, the probability is p_o. In general, $p_i > p_o$ due to the nature of social selfishness. However, when one of the nodes is the source or destination, the message will be forwarded with probability 1.

Considering the message forwarding process in the two communities with social selfishness, we can model it by a two dimensional continuous time Markov chain with state $(m(t), n(t))_{t\geq 0}$, where $m(t)$ $(or\ n(t))$ represents the number of nodes with the message in community V_1 $(or\ V_2)$. Obviously, this Markov chain starts from state $(0,0)$, and has $S = (M+1)\times(N+1)$ transient states. In any transient state $(m(t), n(t))$, the message may be forwarded to the destination, which means the absorbing state, denoted by state (Dst). Therefore, the number of total states is $S+1$. According to the state transition diagram shown in Fig. 1, we can obtain its generator matrix $\mathbf{Q}$ as the following form:

$$\mathbf{Q} = \begin{pmatrix} \mathbf{D} & \mathbf{R} \\ \mathbf{0} & \mathbf{0} \end{pmatrix}, \tag{1}$$

where sub-matrix $\mathbf{D}$ is an $S\times S$ matrix with element $D_{i,j}$ as the transition rates from transient state (i) to state (j), R is a $1\times S$ matrix with element $R_{i,Dst}$ meaning the transition rate from transient state (i) to the absorbing state (Dst). The left $\mathbf{0}$ matrix is a $1\times S$ vector with all element 0 meaning zero transition rates from the absorbing state to transient states. The right $\mathbf{0}$ matrix degenerates to a single 0 element representing the negative sum of the left $\mathbf{0}$ vector. According to the epidemic routing process controlled by the social selfishness, we can obtain the transition rates $\{q_{i,j}\}$ as follows:

$$\begin{cases} D\{(m+1,n)|(m,n)\} = (M-m)(\lambda + mp_i\lambda_i + np_o\lambda_o), \\ \qquad\qquad for\ n\in[0,N], m\in[0,M-1]; \\ D\{(m,n+1)|(m,n)\} = (N-n)(\lambda + mp_o\lambda_o + np_i\lambda_i), \\ \qquad\qquad for\ n\in[0,N-1], m\in[0,M]; \\ R\{(Dst)|(m,n)\} = (m+n+1)\lambda, \\ \qquad\qquad for\ n\in[0,N], m\in[0,M]; \\ D\{(m,n)|(m,n)\} = -D\{(m+1,n)|(m,n)\} - \\ \qquad D\{(m,n+1)|(m,n)\} - R\{(Dst))|(m,n)\}, \\ \qquad\qquad for\ n\in[0,N], m\in[0,M]. \end{cases}$$

B. Performance Analysis

Based on the continuous time Markov chain, we consider two system performance metrics. One is the *message delivery delay*, defined as average time the network spends to deliver the message to the destination. The other is the *message delivery cost*, defined as the average number of times that the message has been replicated before being transmitted to the destination. Related to the message delivery cost, we assume that there is some mechanism to signal the network that the message has reached the destination. Therefore, the computed cost does not address the copies keeping on propagating the message needlessly.

1) Message Delivery Delay: According to the transition matrix $\mathbf{D}$, we can derive the message delivery delay, denoted by D_d, as the following expression [8]:

$$D_d = \mathbf{e}\cdot(-\mathbf{D}^{-1})\cdot\mathbf{I}, \tag{2}$$

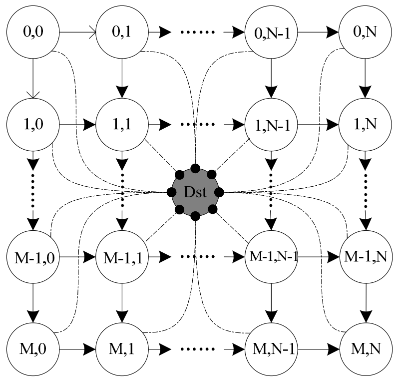

Fig. 1. The continuous time Markov chain for the epidemic routing under two communities with social selfishness. States $(0,0)$ to (M,N) are $(N+1)\times(M+1)$ transient states and state (Dst) is the absorbing state.

where $\mathbf{e}$ is a $1\times S$ vector denoting the initial state probability vector $\mathbf{e} = [1,0,\cdots,0]$, and $\mathbf{I}$ is a $1\times S$ all-one vector $\mathbf{I} = [1,1,\cdots,1]$.

2) Message Delivery Cost: In order to derive the message delivery cost, we should obtain the transition probability from the transient state (i) to the absorbing state (Dst). For this purpose, we consider the embedded Markov chain of the generator matrix $\mathbf{Q}$, denoted by $\mathbf{P}$. Its element $p_{i,j}$ is expressed as follows:

$$p_{i,j} = \begin{cases} -q_{i,j}/q_{i,i},\ j\neq i; \\ 0,\ j=i. \end{cases}$$

$\mathbf{P}$ denotes the one step transition probability matrix, and consequently, the transition probability from state $(0,0)$ to state (Dst), denoted by $\mathbf{P}_{1,S+1}$, is $\mathbf{P}_{1,S+1} = p_{1,S+1}$. $\mathbf{P}^2$ is the two step transition probability matrix. Thus, the transition probability from state $(0,0)$ to state (Dst) via state $(1,0)$ or $(0,1)$ is $\mathbf{P}^2_{1,S+1}$. Therefore, we have the average message delivery cost as follows:

$$C_d = \sum_{i=1}^{M+N} i\cdot\mathbf{P}^i{}_{1,S+1}. \tag{3}$$

III. Numerical Results

In this section, we quantify the performance of delivery delay and delivery cost influenced by social selfishness derived from the proposed model. To set the parameters of contact rates $\tilde{\lambda}$, we use the *Cambridge* trace dataset [11], which is gathered mainly by two group of students of undergraduate year 2 and year 3 from University of Cambridge. From the traces, we first obtain the individual contact rates of any two nodes using the method in Ref. [9] by average statistics, then average the contact rates of users in the same community and across community, and obtain $\lambda_i = 0.101$ $(contacts/hr)$ and $\lambda_o = 0.051$ $(contacts/hr)$, and set $\lambda = 0.084$ $(contacts/hr)$ by averaging all contact rates. Since we focus on evaluating the impact of social selfishness, we set $p_i = 1$. In order to quantify the influence of social selfishness on the performance, we define a metric of *selfish factor*, denoted by f, as follows:

$$f \propto \left(\alpha\,(1-p_o)\,,\ \beta\frac{\min(M,N)}{M+N}\right), \tag{4}$$

where α and β are the positive multiplicators.

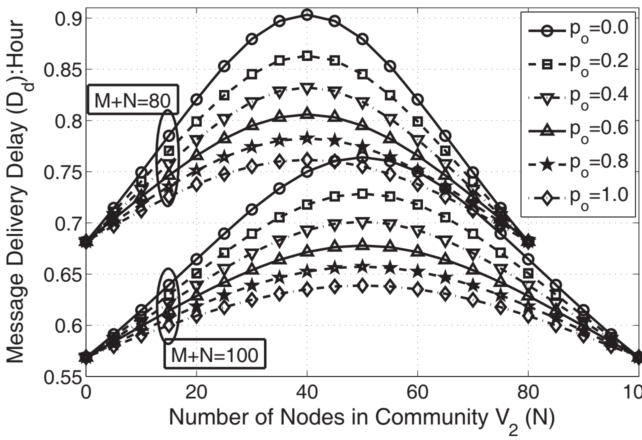

Fig. 2. Numerical results of message delivery delay.

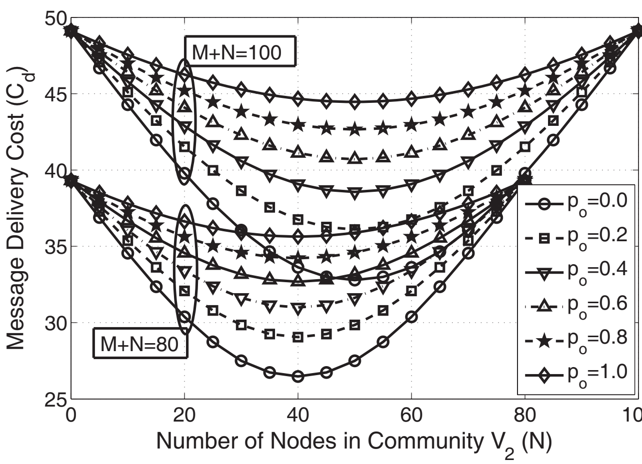

Fig. 3. Numerical results of message delivery cost.

Fig. 2 shows the numerical results of message delivery delay expressed by Equation (2). From the results, we can observe that as the number of nodes in community V_2 (N) increases from 0 to (M+N)/2, the delivery delay of all curves with given p_o increases. This is because the increase of N implies the growth of the selfish factor f when $N < M$. When N is more than half of the total nodes, the delay decreases. When increasing the selfish factor f by decreasing the outside transmission probability p_o from 1 to 0, the delivery delay is increased by 8.9% on average. The maximum delay is obtained at $N = M$ and $p_o = 0$, where the number of cross-community contacts become maximal and the impact of p_o is maximized. From these two points of view, we observe that social selfishness deteriorates the performance of delivery delay. Fig. 3 shows the numerical results of message delivery cost expressed by Equation (3). We can observe that the larger the selfish factor f, by increasing either $1 - p_o$ or $\frac{\min(M,N)}{M+N}$, the less the delivery cost. When p_o decreases from 1 to 0, the delivery cost is reduced by 12.1% on average. Consequently, from this point, we obtain that the social selfishness enhances the system performance in terms of delivery cost. Therefore, in the networks without strict requirement of delivery delay, the social selfishness can be used to decrease the delivery cost.

To investigate the deceleration ratio of delivery delay and

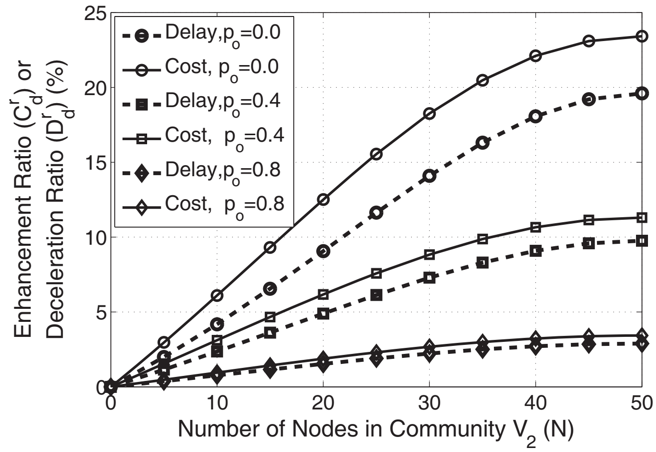

Fig. 4. Numerical results of delivery deceleration ratio and cost enhancement ratio with different outside forwarding probability p_o.

enhancement ratio of delivery cost, we define two related metrics, *delay deceleration ratio* and *cost enhancement ratio*, denoted by D_d^r and C_d^r respectively, as follows:

$$D_d^r = \frac{D_d(p_o) - D_d(1)}{D_d(1)},\ C_d^r = \frac{C_d(1) - C_d(p_o)}{C_d(1)}. \quad (5)$$

We set $M + N = 100$ and plot the results in Fig. 4. From the results, we can obtain that both D_d^r and C_d^r increase with the increasing of selfish factor f. Comparing D_d^r and C_d^r with the same f, C_d^r is always larger than D_d^r, and the larger the selfish factor f, the larger the gap between D_d^r and C_d^r. When f achieves maximum at $N = 50$ and $p_o = 0$, the gap is about 3.8%. Therefore, we come to the conclusion that DTN is quite robust to social selfishness. Although it increases the message delivery delay, there is more reducing of message delivery cost.

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